

A New Measurement of Cosmic Ray Composition at the Knee

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ABSTRACT

The Dual Imaging Cerenkov Experiment (DICE) was designed and operated for making elemental composition measurements of cosmic rays near the knee of the spectrum at several PeV. Here we present the first results using this experiment from the measurement of the average location of the depth of shower maximum, $\langle X_{max} \rangle$, in the atmosphere as a function of particle energy. The value of $\langle X_{max} \rangle$ near the instrument threshold of ~ 0.1 PeV is consistent with expectations from previous direct measurements. At higher energies there is little change in composition up to ~ 5 PeV. Above this energy $\langle X_{max} \rangle$ is deeper than expected for a constant elemental composition implying the overall elemental composition is becoming lighter above the knee region. These results disagree with the idea that cosmic rays should become on average heavier above the knee. Instead they suggest a transition to a qualitatively different population of particles above 5 PeV.

Subject headings: cosmic rays, supernova remnants, instrumentation:detectors, ISM:abundances

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1. Introduction

Observations of cosmic rays have presented several puzzles which have been resolved by detailed measurements of composition, both elemental and isotopic. The present picture of the production of the bulk of cosmic rays by diffusive shock acceleration in supernova remnants is attractive since it appears to be the only energy source powerful enough to sustain this particle population in our galaxy. There is also a strong theoretical link between the observed energy spectra of the sources and the predictions of strong shock acceleration, (Axford et al. 1977, Bell 1978, Blandford and Ostriker 1978, Krymsky 1977). However, there is still no direct evidence that the bulk of cosmic rays are produced by this mechanism. Searches for the TeV gamma emission which should be produced by the high energy nuclei at these sites are in progress, (see e.g. Lessard et al. 1995). The supernova remnant shock acceleration in its most straightforward form produces a maximum energy for particles accelerated by this mechanism to be close to $Z \times 0.1 \text{ PeV}$ (Lagage and Cesarsky 1983). This limit is determined by the average acceleration rate and the mean lifetime of the strong shock in a typical supernova event. The 'knee' in the cosmic ray flux, where the energy spectrum becomes steeper around several PeV, could well be related to this theoretical limit. Some workers (see e.g. Axford 1994) have suggested that cosmic rays above the knee are produced by the secondary acceleration of high energy particles from supernova by weaker shocks in the Galaxy. This would result in an increase in the average mass of cosmic rays through the knee. If the cosmic rays from shock acceleration in Galactic supernovae are more strictly limited to the knee energy then a second population of particles must be present to produce the fluxes of cosmic rays observed at higher energies, possibly of extragalactic origin as suggested by Protheroe and Szabo 1992. As with other properties of cosmic rays a measurement of composition in this energy range can be used to detect these changes and provide the information needed to investigate the origins of cosmic rays above the knee.

While direct detection above the atmosphere remains the most desirable method for composition determination, the fluxes of particles in this energy range are so small that a space instrument large enough to collect a good statistical sample up to 10 PeV has not yet been flown. Indirect detection

of cosmic rays, through measurements of air showers produced in the atmosphere, can easily supply sufficient collecting power but these methods generally have substantially reduced mass and energy resolution. The properties of the originating cosmic ray nucleus becomes clouded by the huge number of interactions in the air shower. The reconstruction of the mass of the incoming nucleus from measurements of the shower distributions at ground level is also subject to systematic errors resulting from imperfections of the Monte Carlo modelling of air showers. DICE is a ground based air shower experiment which is designed to have as little reliance as possible on the details of the Monte Carlo simulations and to have the capability of comparison of results with direct measurements at 0.1 PeV to provide an assessment of overall systematic errors.

2. Experiment Description

The two DICE telescopes (see Boothby et al. 1995, Boothby et al. 1997) are located at the CASA-MIA site in Dugway, Utah (described in Borione et al. 1994). They each consist of a 2m diameter $f/1.16$ spherical mirror with a focal plane consisting of 256 close packed 40mm hexagonal photomultipliers (PMTs) to provide $\sim 1^\circ$ pixels with a field of view of $16^\circ \times 13.5^\circ$ centered about the vertical. The two telescopes are on fixed mounts separated by 100m located near the center of the CASA site.

Cosmic ray events within the field of view produce a focal plane image at the photomultiplier cluster which is an intensity pattern of Čerenkov light coming from the air shower. When the direction of the air shower and the distance of the shower core from the telescopes are known, simple geometry can be used to reconstruct the amount of light received from each altitude of the shower. The amount of Čerenkov light produced at each altitude is strongly correlated with the number of electrons at that atmospheric depth. This is used to estimate the electron size as a function of depth in the atmosphere from which X_{max} can be determined. This procedure is essentially geometrical and is independent of Monte Carlo simulations except for calculations which determine the angular distribution of Čerenkov light around the shower axis.

Here we report on the analysis of shower maxima from the images in the DICE clusters using the independent shower geometry established by the CASA air shower array. The accuracy of the CASA geometry

for each shower in the knee region is $< 5\text{m}$ for shower core location on the ground and $< 0.6^\circ$ for shower trajectory direction (Borione et al. 1994). The absolute alignment of the DICE clusters relative to the vertical has been determined to an accuracy of $\sim 0.1^\circ$ by detection of transits of stars across the DICE apertures.

The events which trigger both DICE telescopes and the CASA array have data which are recorded separately and later matched by comparing the times of each event. The trigger rates are typically 0.1Hz and the time information is accurate to $\sim 1\text{ms}$, the fraction of mismatched events in the raw data is $< 1\%$. During analysis these mismatches are further suppressed by (i) the requirement that shower images in DICE lie in the direction of the CASA event, (ii) the reconstructed shower maxima from the two DICE telescopes using the CASA geometry are in agreement. These analysis cuts further suppress the mismatches by a factor of ~ 1000 , resulting in an overall background level of $\sim 10^{-5}$.

3. Data Collection and Analysis

DICE has been operational at the Dugway site since summer 1994, this analysis comes from the period July 1994 - December 1995. Data is collected during clear, moonless nights. The events analyzed here come from 914 hours of operation, corresponding to $\sim 7\%$ livetime during this period. The effective geometrical acceptance aperture of DICE with the data cuts used is $\sim 2000\text{ m}^2\text{sr}$ making the overall collecting power at high energies near $80,000\text{ m}^2\text{sr days}$. This allows a statistically valuable measurement of composition up to energies of $\sim 10\text{ PeV}$. The trigger threshold and logic of the DICE PMT clusters produces some trigger inefficiency for showers below $\sim 800\text{TeV}$, this introduces a small bias in this region which is discussed later.

For each collected event the Čerenkov images are fit by translating the PMT amplitudes into a sequence of Čerenkov luminosities and hence shower electron sizes versus atmospheric depth (g/cm^2) by using the shower geometry from CASA and the distribution of Čerenkov light about the shower axis predicted from the CORSIKA air shower Monte Carlo (Knapp et al. 1996). These shower development curves are fit to a longitudinal development function from which the shower maximum, size and width are determined. Independent fits are made for each of the two DICE

clusters so that a consistency check can be made between the two sets of shower fit parameters. For the shower maxima the difference distribution between the fits from the two sites has an rms width of $\sim 65\text{g}/\text{cm}^2$, after correcting for correlations associated with the uncertainties in the geometry the dual site rms resolution for a single event is $\sim 45\text{g}/\text{cm}^2$. Showers which have cores located equidistant from each cluster produce amplitudes of Čerenkov light which should be similar in each cluster. The difference distribution of these events shows an rms width of $\sim 26\%$ implying a dual site resolution of $\sim 13\%$ for the Čerenkov size. The energy of each event is estimated from the mean of the independent values derived from the light intensity at each cluster. The amount of Čerenkov light collected at each cluster is corrected by a factor of $B \times \exp(r/r_0)$ where B is a normalization factor, r_0 is a scale length, and r is the distance from the cluster to the core. The values of r_0 and B are determined from CORSIKA. These do not have a large dependence on the mass of the primary nucleus for the core distances of $100\text{m} < r < 225\text{m}$ used in this analysis. In this analysis the value $r_0 = 82.5\text{m}$ is used and the value of B is taken to have a single value for all events. This introduces a mass dependent error in the energy estimate which is $\sim 10\%$. The largest uncertainty in the energy estimate is in the conversion from PMT pulse height to Čerenkov photon density since a number of factors including mirror reflectivity and PMT quantum efficiency need to be accurately known. This overall systematic error in the energy scale is estimated to be $\pm 20\%$.

The following data cuts are made: (i) The core of the shower lies at a distance $100\text{m} < r < 225\text{m}$ from both DICE clusters. (ii) The fits of the longitudinal developments in each DICE telescope have reduced $\chi^2 < 3$. (iii) The X_{max} from the two sites agree within $75\text{g}/\text{cm}^2$. (iv) The shower direction is within 5° of the vertical. The measurements of X_{max} and energy from the two clusters are averaged to give overall values for each shower. Values of X_{max} are binned versus energy using the boundaries shown in Table 1. To gain some confidence for the accuracy of the energy scale and the overall detection efficiency estimates an energy spectrum of cosmic rays has been derived from the data by calculating absolute fluxes. The dominant efficiency correction for this work is the trigger scheme for each photomultiplier cluster. A simulation which includes the trigger logic and air shower characteristics derived from samples of air showers produced

by CORSIKA is used to derive the various efficiencies and the acceptance geometry of DICE. The exposure livetime can be directly derived from the data since at each minute of operation the cluster electronics records the livetime for that period. The cluster deadtime is small, typically $<1\%$. A combination of the efficiencies, geometry and livetime is used to derive the fluxes of particles by a matrix deconvolution technique using the monte carlo.

4. Results

The absolute fluxes of cosmic rays obtained for these data are shown in Figure 1, note the fluxes are multiplied by an overall factor of $E^{2.75}$. Also shown for comparison are results from some previous air shower experiments which use electron sizes at ground level to estimate the energy. The DICE data energy spectrum has been calculated assuming a mixed composition model of the type discussed by Swordy 1995. This model provides a composition at 1PeV of $\sim 40\%$ H, $\sim 30\%$ He, and $\sim 30\%$ heavier nuclei and at 10PeV $\sim 20\%$ H, $\sim 20\%$ He and $\sim 60\%$ heavier nuclei. Also shown are energy spectra reconstructed under the assumption that either (a) the particles are all protons or (b) particles are all iron nuclei. As can be seen these do not change the fluxes or slopes significantly. There is a distinct change in slope near ~ 4 PeV which is consistent with the existence of the ‘knee’ in this region. Since the model used to reconstruct the energy spectrum is heavier at high energies than suggested by the values of $\langle X_{max} \rangle$ measured by DICE, this could introduce a systematic bias which might enhance the derived fluxes above ~ 5 PeV. This enhancement is at maximum 10%, less than the statistical precision of the fluxes in this region. The possible effect of a miscalibration of the energy scale is shown by the length of the vertical bar to the left of the picture. This represents the overall systematic uncertainty in flux from the DICE measurements corresponding to an energy scale shift of $\pm 20\%$. The size of the trigger inefficiency correction becomes large below ~ 400 TeV making fluxes derived from events in this region more uncertain than this systematic limit. The overall DICE trigger efficiency is a combination of the cluster trigger efficiency and the total light intensity produced at the cluster. DICE is therefore capable of triggering with high efficiency on bright events with energies > 2 PeV out to the maximum extent of the data cuts at $r = 225$ m. The light from lower energy particles showers is not intense enough

to always provide triggers at this distance, the trigger simulation is used to calculate the amount of data lost by this effect. At 500TeV the overall detection efficiency is $\sim 50\%$.

The variation of $\langle X_{max} \rangle$ with energy is given in Table 1. The third column shows the raw values and the next column shows the values of the correction, δ , for trigger and geometry bias. The trigger bias arises from the fact that near threshold protons are more likely to trigger DICE than iron nuclei because they produce more Čerenkov light. The size of this correction is derived from the trigger simulation which incorporates information from CORSIKA on the variation of the intensity of light with incoming particle energy and mass. The geometry bias of this correction is associated with the finite pixel resolution of DICE. At high altitudes the shower structure becomes difficult to determine because the shower development occurs on angular scales which are comparable to the DICE pixel resolution. The combination of these effects produces an overall correction which is relatively large for the first energy bin but which becomes small at higher energies. These data are plotted in Figure 2, the vertical errors are statistical, the horizontal correspond to the systematic error in energy estimate discussed above. Also shown is the results of direct measurements at 0.1PeV converted by the CORSIKA Monte Carlo to a value which corresponds to the expected mean shower maximum for this composition. The small dotted lines show how the mean shower maximum should behave for pure protons or iron nuclei based on CORSIKA. The DICE results lie between these extremes and agree well with the extrapolation from direct measurements at the lower energies, shown as the large dashed line. There is little apparent change in mass composition through the energy range of most of these data. The indications are that the composition becomes lighter above ~ 5 PeV although the statistics are limited. The comparison of the measured distribution widths of X_{max} with the widths of simulations for pure protons and pure iron nuclei including the DICE detector response are given in Table 2. These are consistent with the movement of the mean shower maximum with energy.

The first results from DICE show no evidence for an increase in the average mass of cosmic rays in the knee region. These lower energy results of DICE are consistent with recent measurements which use the *intensity distribution* of Čerenkov light at ground level to show no change in composition up to 1PeV

(Plaga et al. 1995). An increase in mass has been expected somewhere near the knee because any process which involves a steepening of magnetic rigidity (momentum/charge) spectra of the particles, either in the sources or elsewhere, naturally leads to an overall increase in the mass of a population of particles measured by energy/particle. It is difficult to escape the conclusion from Figure 2 and Table 2 that a simple rigidity steepening of this type is probably not responsible for the ‘knee’ of the cosmic ray spectrum. Although these measurements indicate a transition to a more proton-rich source of particles, in the present results this is only a $\sim 3\sigma$ effect which should be verified by further measurements. If confirmed, this transition suggests we are reaching an energy scale where conventional supernova shock acceleration and propagation through the galaxy is no longer the dominant source. We may be beginning to see a population of much older particles confined in the halo of our galaxy or possibly of extragalactic origin.

5. Acknowledgements

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TABLE 1
DICE MEASUREMENTS OF $\langle X_{max} \rangle$

Energy bin (PeV)	Events	$\langle X_{max} \rangle$ raw (g/cm ²)	δ^a (g/cm ²)	Median Energy ^b (PeV)	$\langle X_{max} \rangle$ (g/cm ²)
0.2 - 0.4	6132	474	-12	0.25	462 \pm 2
0.4 - 0.7	3708	479	-1	0.5	478 \pm 2
0.7 - 1.5	2279	501	+2	1.0	503 \pm 2
1.5 - 3.0	740	534	+3	2.0	537 \pm 3
3.0 - 5.0	212	549	+3	4.0	552 \pm 4
5.0 - 8.0	70	587	+3	6.0	590 \pm 10
8.0 - 15.0	37	628	+3	10.0	631 \pm 14

^aThis trigger correction is discussed in the text

^bThe energy scale has an estimated systematic error of $\pm 20\%$

TABLE 2
DICE MEASUREMENTS OF THE WIDTHS OF X_{max} COMPARED WITH SIMULATIONS FOR PROTONS AND IRON NUCLEI

Median Energy ^a (PeV)	DICE $\sigma(X_{max})$ (g/cm ²)	Sim. $\sigma(protons)$ (g/cm ²)	Sim. $\sigma(iron)$ (g/cm ²)
1.0	73 \pm 1	87	66
2.0	66 \pm 2	83	49
4.0	58 \pm 4	82	41
6.0	82 \pm 12	81	40
10.0	85 \pm 20	79	40

^aOnly energies where the trigger bias is small are included

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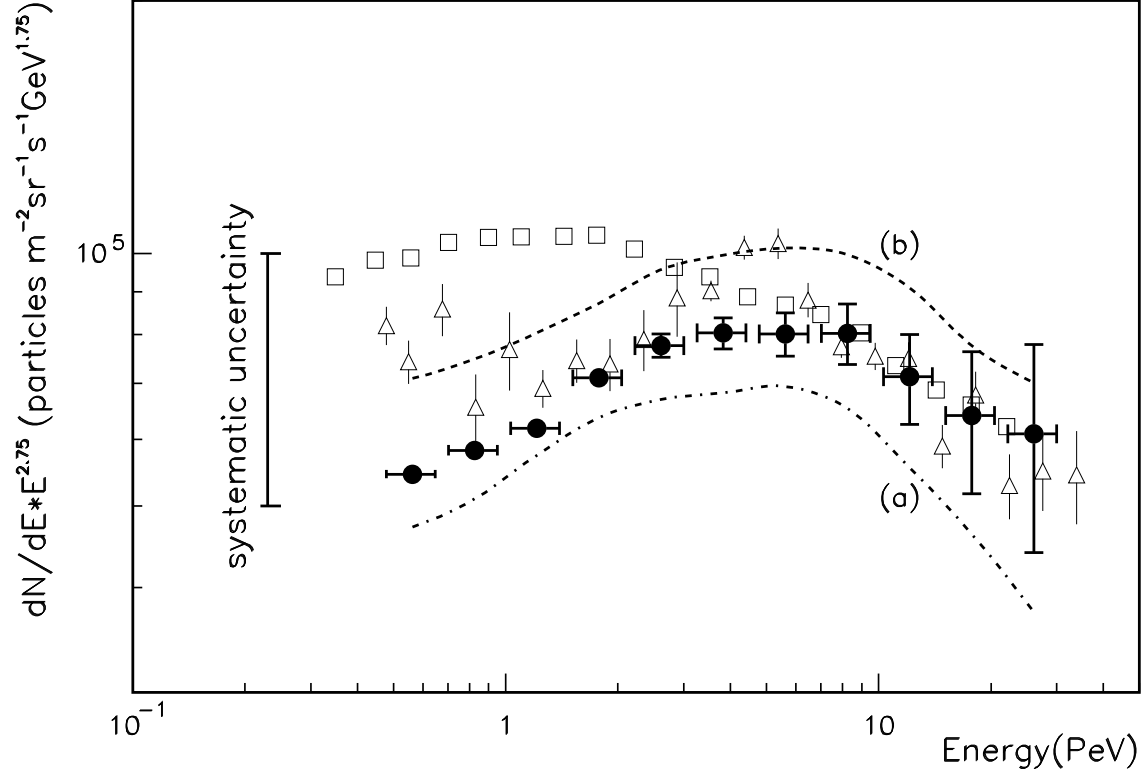


Fig. 1.— The absolute fluxes of particles measured by DICE as filled circles compared with previous measurements (triangles -Nagano et al. 1984, squares -Amenomori et al. 1996). Note the fluxes are multiplied by a factor of $(\text{Energy})^{2.75}$. These fluxes were derived assuming the mixed elemental composition from Swordy 1995. Curve (a) shows the fluxes produced by assuming an all-proton composition, curve (b) shows fluxes assuming an all-iron composition. The vertical bar on the left represents the systematic variation of the flux levels because of uncertainty in the overall energy scale. The DICE fluxes have power law indices of -2.55 ± 0.01 below 4PeV and -2.92 ± 0.1 above 4PeV

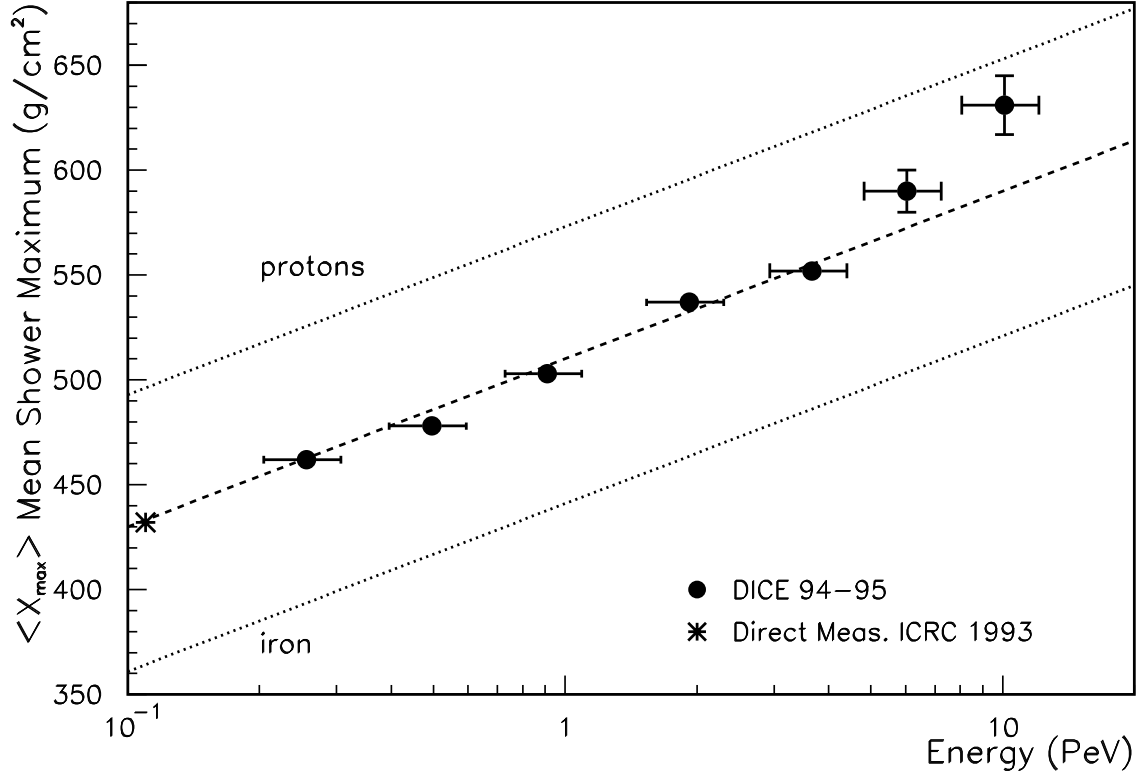


Fig. 2.— The variation of the mean depth of shower maximum ($\langle X_{max} \rangle$) with particle energy measured by DICE. The star is a conversion of an assembly of direct measurements (Swordy 1994) to the expected $\langle X_{max} \rangle$ using the CORSIKA Monte Carlo - the long dashed line shows how $\langle X_{max} \rangle$ scales with energy for a constant elemental composition. The upper dotted line is the $\langle X_{max} \rangle$ expected for all-proton composition and the lower dotted line is the value expected for all-iron composition.